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Semi-Annual Report

Grant No. NAG-1-349

DIGITAL CONTROL SYSTEM FOR SPACE STRUCTURAL DAMPERS

Submitted to:

National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

Attention: Dr. Garnett C. Horner
SDD, MS 230

Submitted by:

J. K. Haviland
Professor

Report No. UVA/528224/MAE84/101

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SCHOOL OF ENGINEERING AND APPLIED SCIENCE

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

UNIVERSITY OF VIRGINIA
CHARLOTTESVILLE, VIRGINIA 22901

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ABSTRACT

This is a semi-annual progress report on a study of digital control systems for space structural dampers, also referred to as "inertia" or "proof-mass" dampers. Under work performed to date, a recently developed concept for a damper has been improved by adding a small taper to the proof-mass, and using a proximeter to determine position. Also, an experimental damper has been built using a three-inch stroke in place of the standard one-inch stroke. Initially, an analog controller was used; this has now been replaced by an independent digital controller slaved to a TRS-80 Model I computer, which also serves as a highly effective, low-cost development system. An overall system concept for the use of proof-mass dampers is also presented.

SECTION I

INTRODUCTION

The active damper design which is the subject of the present study was originally proposed under NASA Grant No. NAG-1-137-1. During the period of this grant, the prototype damper shown in Figure 1 was developed, and development of the analog control system shown in Figure 2 was initiated. Under a further purchase order from NASA, No. L-46164B, the damper was redesigned as in Figures 3 and 4. Twelve of these dampers were delivered to NASA.

Under the current grant, NAG-1-349, a prototype digital control system has been developed, and a prototype elongated damper has been built having a three-inch stroke as contrasted with the one-inch stroke of the original. Our current thinking on applications to large space structures is that each damper will have an individual microprocessor-driven control system whose gains can be reset by a central computer. Since it is anticipated that future space structures will experience growth during service, as new sections are added, less emphasis has been placed on optimization. It is now assumed that new dampers will be added as new structural sections are added, that these will be connected by bus to a central computer, and that adaptive control methods will be used in a central computer to change gains, or even control law programs, and to detect failures.

During this period, Mr. M. Mallette, a graduate student, has worked in parallel with the work reported here, under NASA Grant No. NGT-47-005-800.

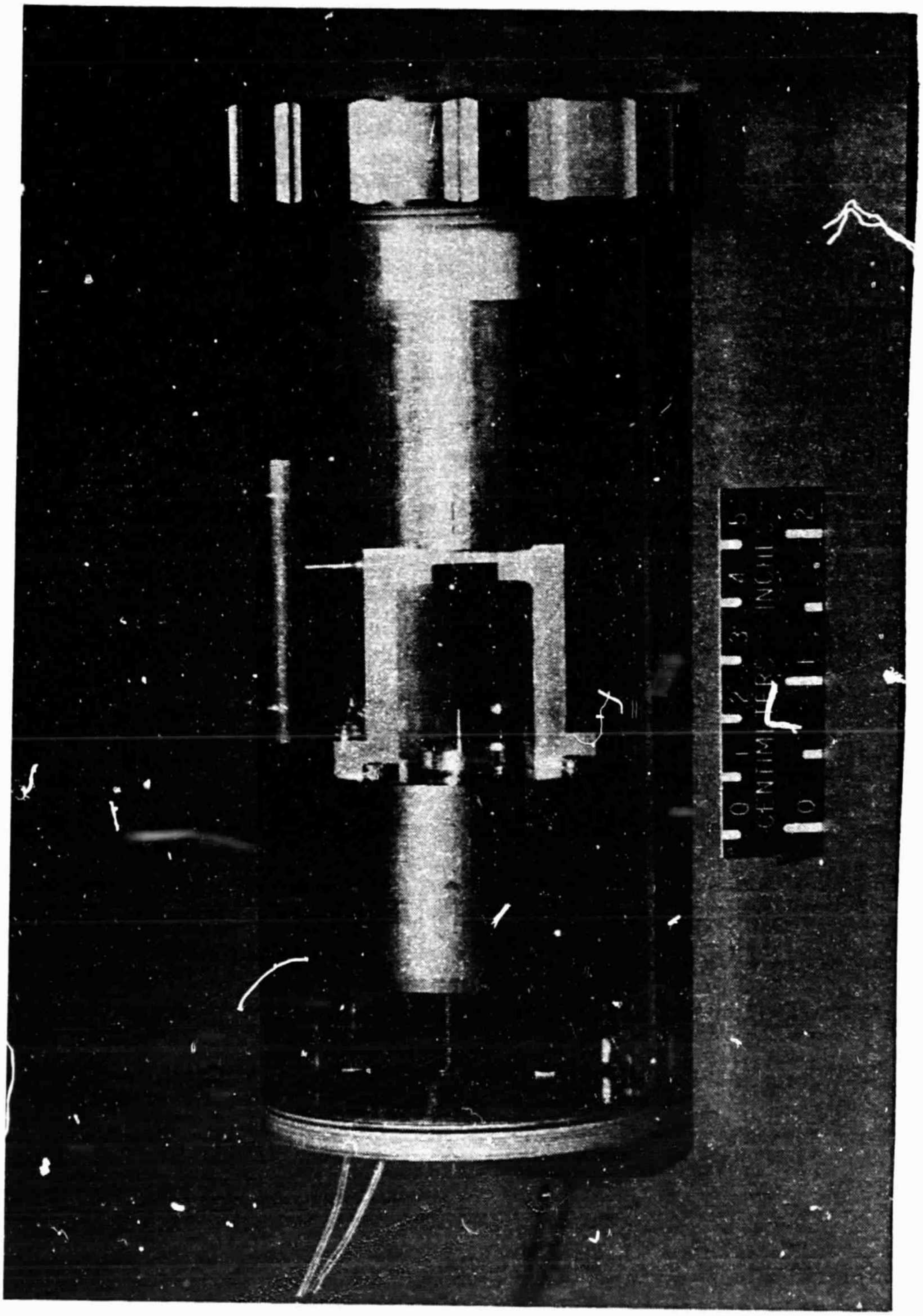

Figure 1. UVA Prototype Inertia Damper

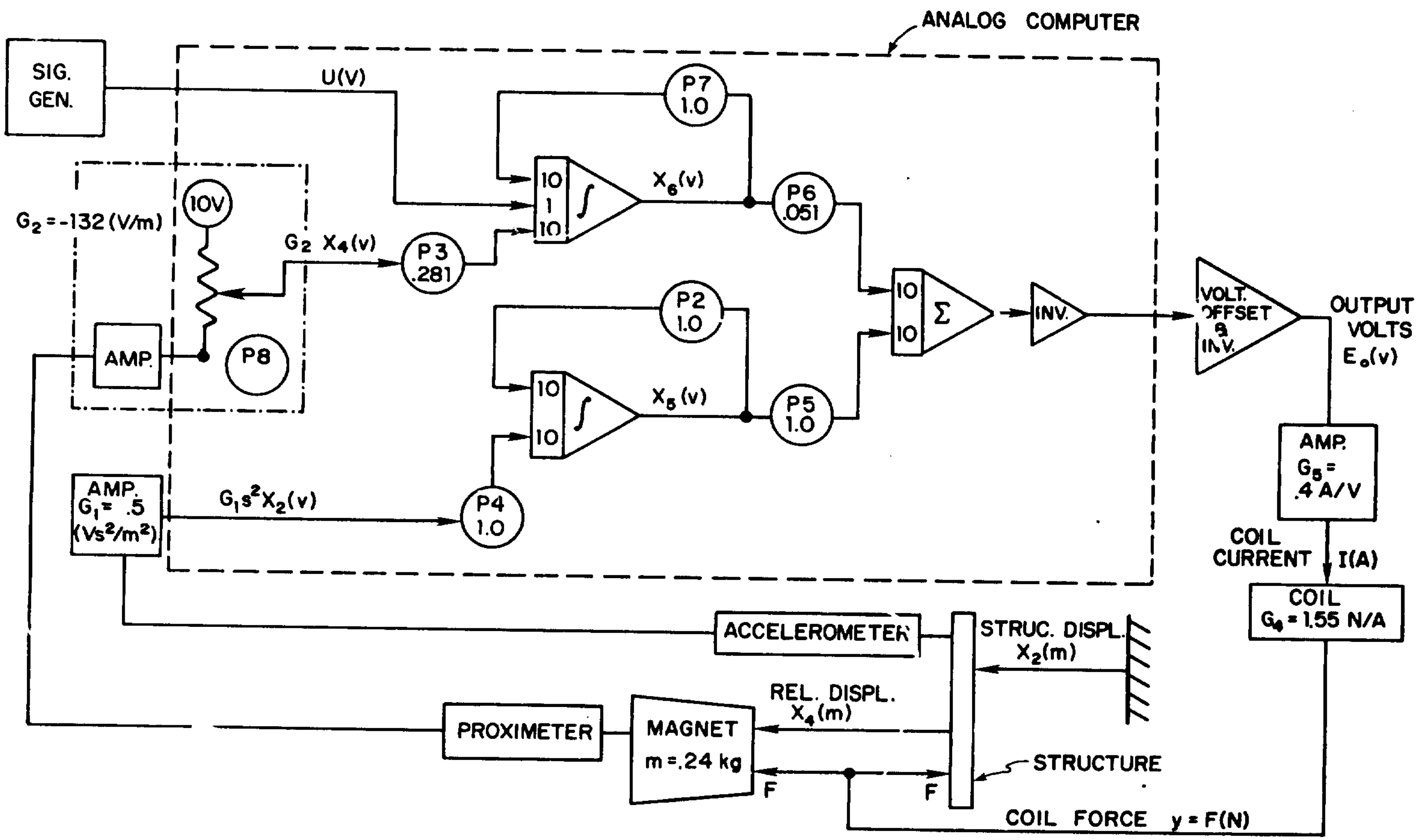

Figure 2. Analog Control System for Inertia Damper

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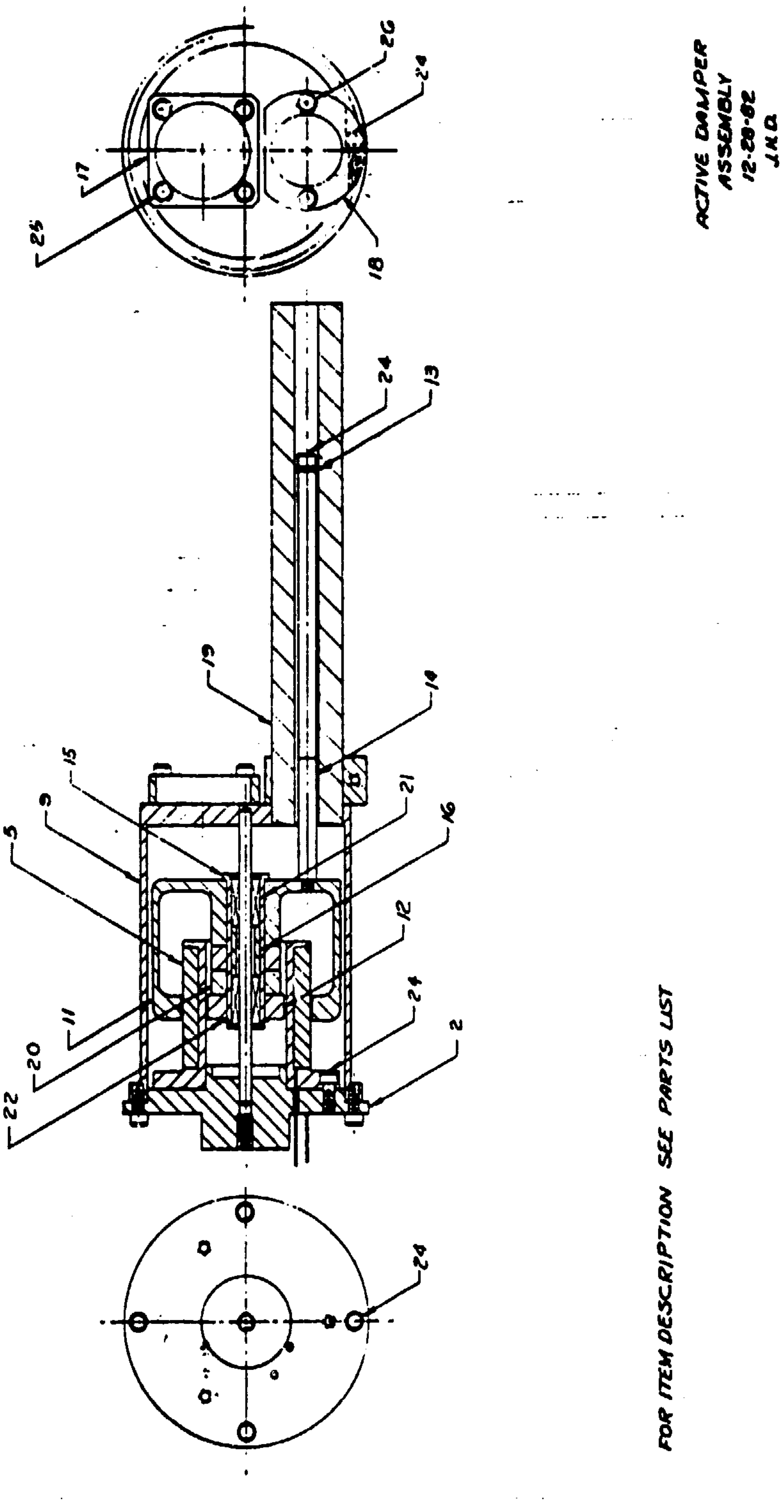

Figure 3. Section of Inertia Damper Supplied to NASA

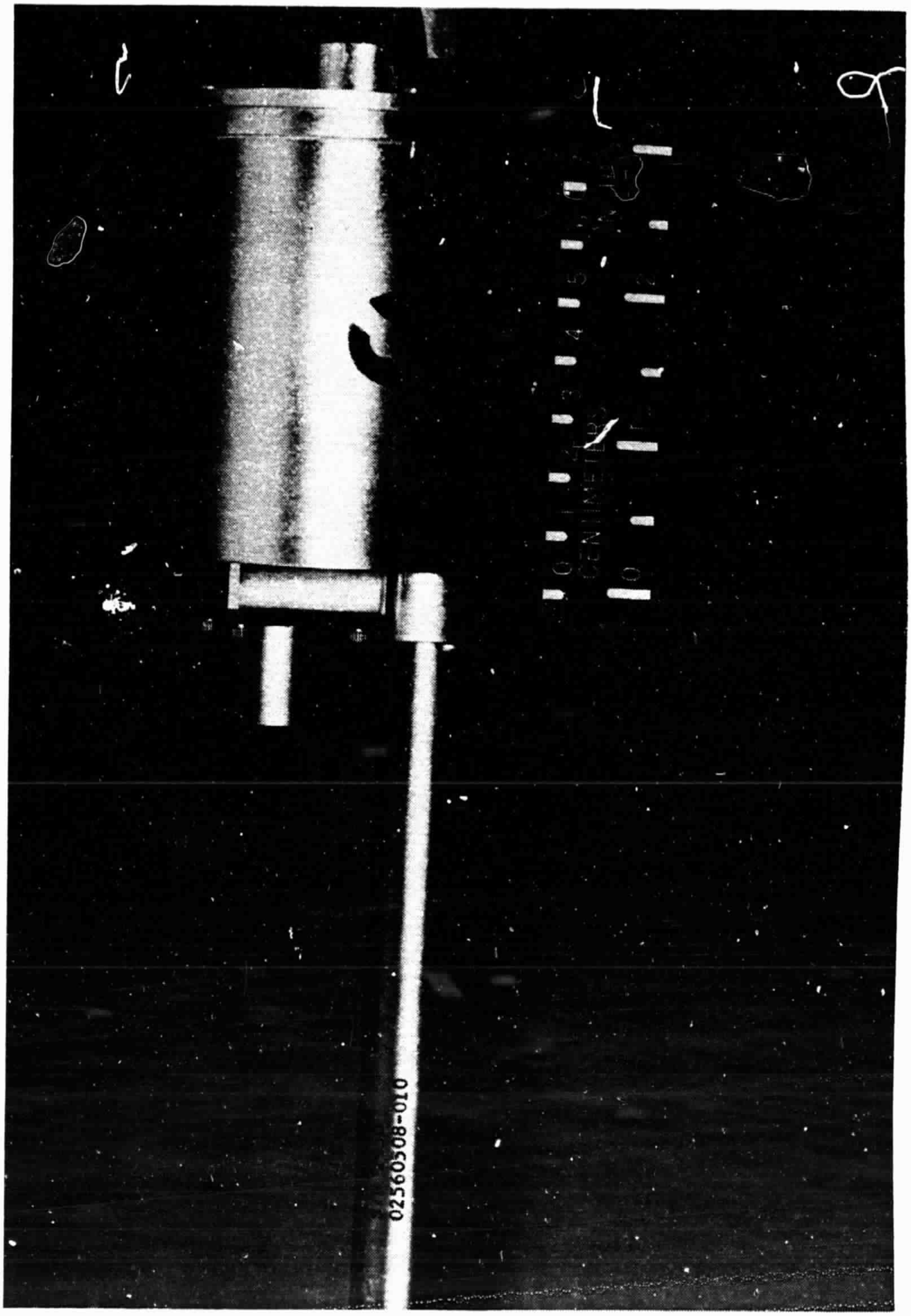

Figure 4. Inertia Damper Supplied to NASA

SECTION II

PROJECT RESULTS

Damper Design

Examples of one-inch and three-inch stroke dampers currently used in the laboratory are shown in Figures 5 and 6. Transparent covers permit their action to be observed at all times. The essential difference between these designs and the design of the dampers delivered to NASA is that the LVDT has been replaced by a proximeter. A small taper has been introduced on the proof-mass body so that its position can be determined by the proximeter.

Analog Control Circuit

The analog control circuit, as finally developed, is shown in Figure 2. Values shown for gains were selected during tests, with the actuator attached to a 15 ft. beam. Equations developed for this circuit are shown in Figure 7; these feature the three transfer functions H_1, H_2 and H_3, which represent coil force due to inputs from the accelerometer, the proximeter, and a signal generator, respectively. The latter is used for testing the system.

A block diagram for the complete system is shown in Figure 8. From this, the equations of Figure 9 were developed. The transfer function H_c is the complex damping coefficient, which limits to the design damping coefficient c at high frequencies.

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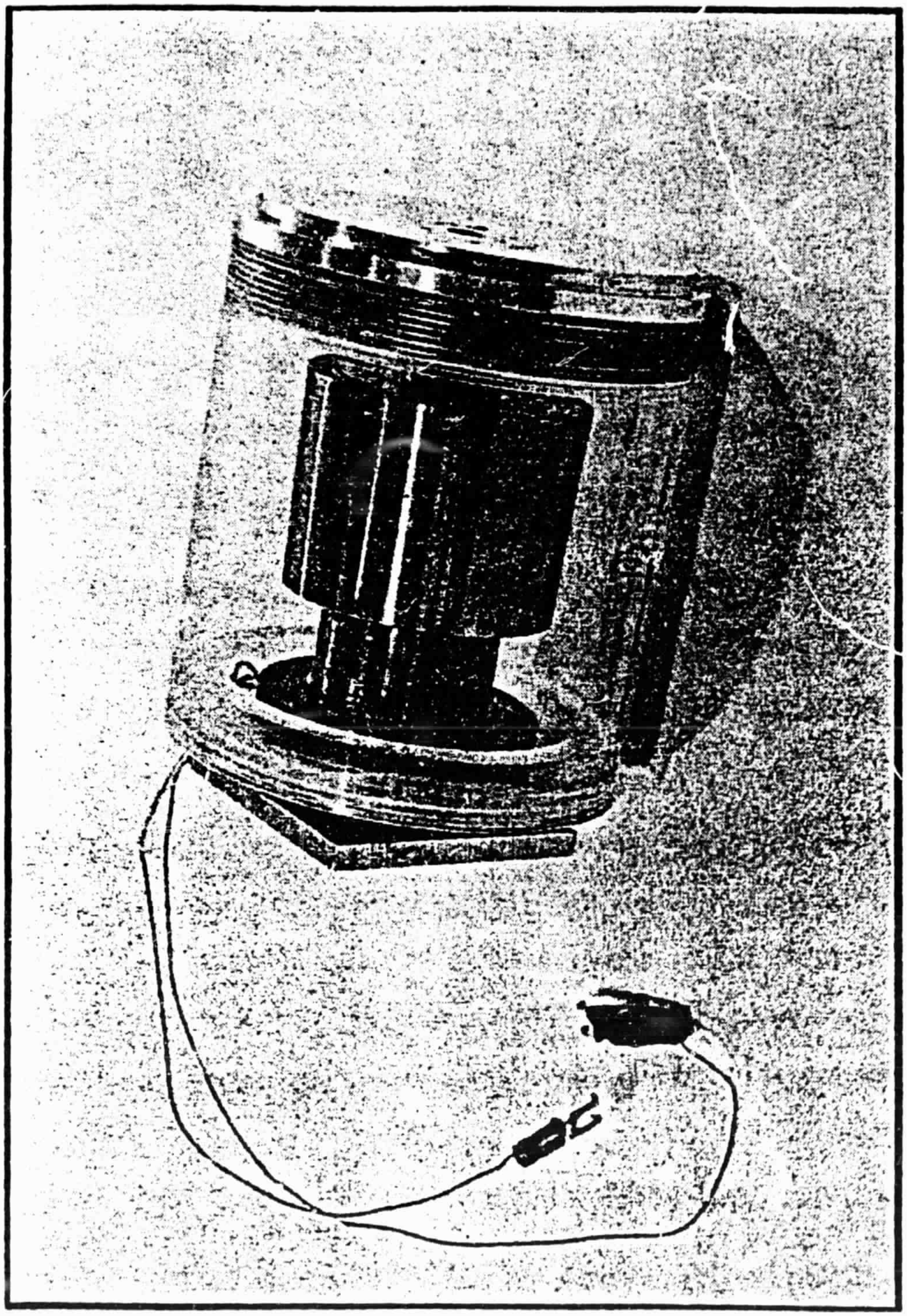

Figure 5. Modified Prototype Damper, One-Inch Stroke

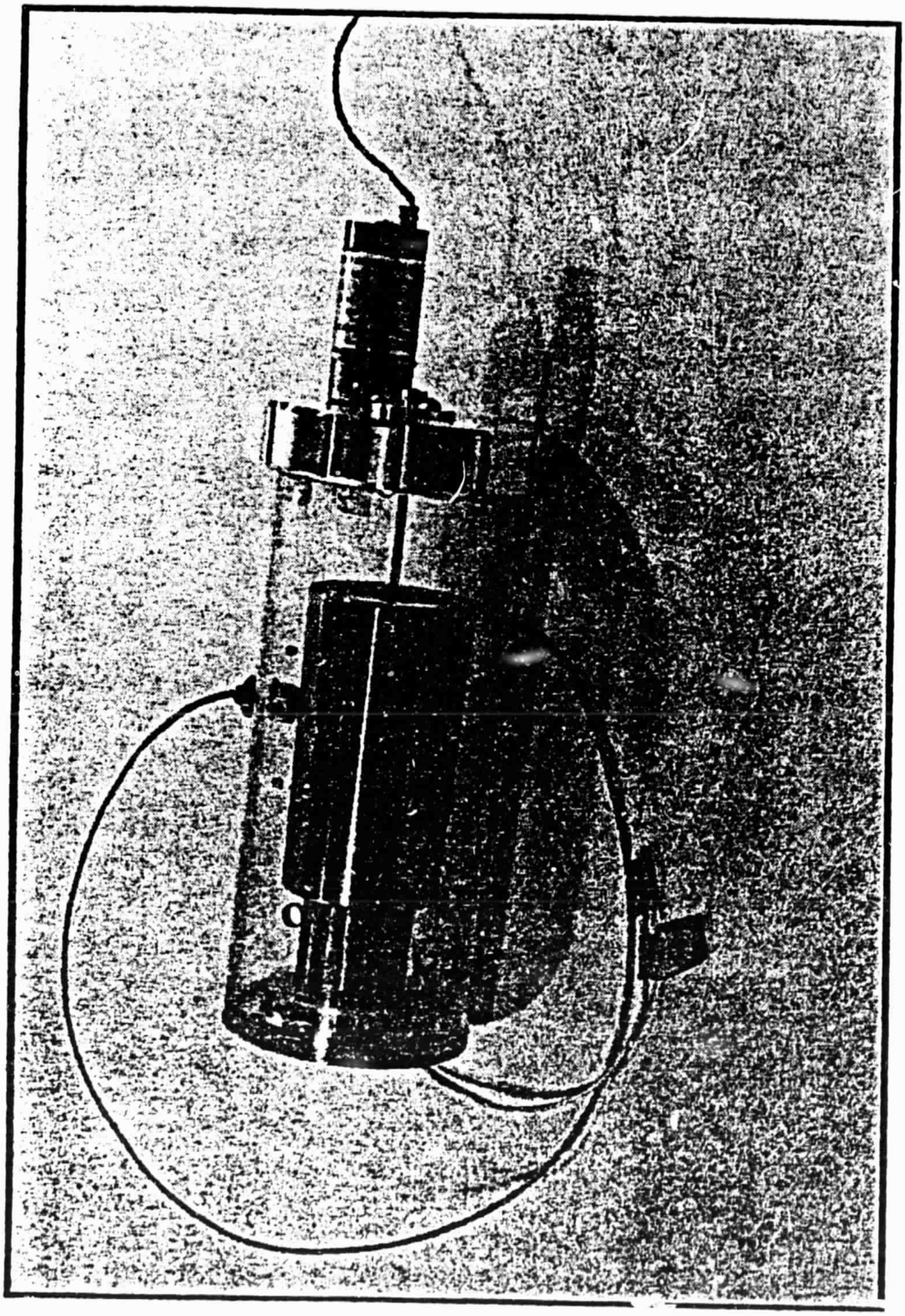

Figure 6. Three-Inch Damper Prototype

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Definitions

x_1 = Structural velocity (m/s)

x_2 = Structural deflection (m)

x_3 = Proof mass velocity (m/s)

x_4 = Proof mass relative displacement (m)

x_5 = Integrator output (v)

x_6 = Integrator output (v)

E_o = Output volts (v)

I = Output current (A)

F = y = Coil force (N)

m = Proof mass (m)

G_1 = Gain of accelerometer (Vs^2/m)

G_2 = Gain of proximeter (v/m)

G_4 = Coil force for unit current (N/A)

G_5 = Gain of coil driver (A/V)

u = Input signal (v)

Equations

$$F = y = H_1x_2 + H_2x_4 + H_3u \quad (N)$$

$$F/ms^2 = x_2 + x_4 \ (m)$$

$$H_1 = \frac{100\ G_1G_4G_5P_4P_5s^2}{s + 10\ P_2} = \frac{cs^2}{s + \omega_a} \quad (N/m)$$

C = Design damping coefficient (Ns/m)

Figure 7. Analog Circuit Summary

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Equations (continued)

ω_a = Roll-off frequency for accelerometer (s^{-1})

$$H_2 = \frac{100\ G_2G_4G_5P_3P_6}{s + 10\ P_7} = -\frac{k\omega_p}{s + \omega_p} \quad (N/m)$$

k = Design stiffness (N/m)

ω_p = Roll-off frequency for proximeter (s^{-1})

$$H_3 = \frac{10\ G_4G_5P_6}{s + 10\ P_7} = \frac{F_o\omega_p}{s + \omega_p} \quad (N/V)$$

F_o = Coil Force for Unit Signal Generator Voltage (N/V)

Typical Values

$G_1 = 0.5\ (Vs^2/m)$; $G_2 = -132\ (V/m)$

$G_4 = 0.4\ (V/A)$; $G_5 = 1.55\ (N/A)$

$H_1 = \frac{31s^2}{s + 10}\ (N/m)$; $C = 31\ (Ns/m)$

$\omega_a = 10(s^{-1})$

$H_2 = \frac{-117}{s + 10}\ (N/m)$; $k = 11.7\ (N/m)$

$\omega_p = 10(s^{-1})$

$H_3 = \frac{0.316}{s + 10}\ (N/v)$; $F_o = 0.0316\ (N/V)$

Figure 7. Analog Circuit Summary (Continued)

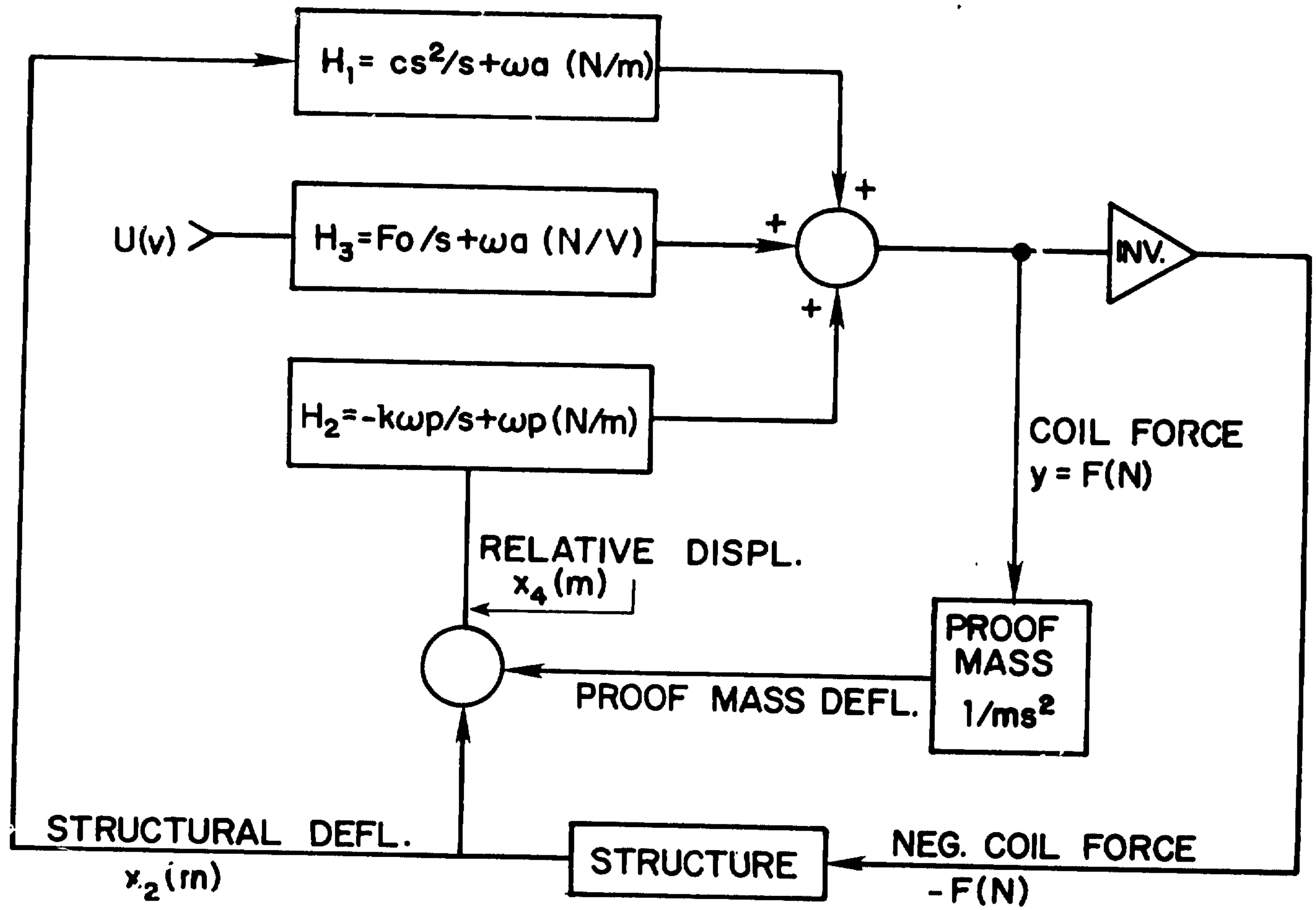

Figure 8. Block Diagram of Analog Circuit

Given:

$$F = H_1 x_2 + H_2 x_4 + h_3 u \quad (N)$$

$$F = ms^2(x_4 + x_2) \quad (N)$$

$$F = \frac{H_1 - H_2}{1 - H_2/ms^2} x_2 + \frac{H_3}{1 - H_2/ms^2} u = H_c s x_2 + H_u u \quad (N)$$

$$H_c = \frac{cs^3(s + \omega_p) + k\omega_p s(s + \omega_a)}{s^2(s + \omega_a)(s + \omega_p) + k\omega_p(s + \omega_a)/m} \quad (Ns/m)$$

$= $ True damping coefficient

Figure 9. Analysis of Block Diagram for Analog Circuit

Digital Control Circuit

The digital control circuit now under development is shown in Figure 10. Input signals are converted to the range 0-5 V, digitized to one-byte values, and read into a TRS-80 Model I computer. Output from the computer is reconverted to a 0-5 V signal, and is used to drive a NASA developed current amplifier which drives the coil. Equations developed for this system are shown in Figure 11.

Values for the constants in the expression for H_1, H_2 have the same values as those in Figure 7 when the appropriate values for G_a, G_ρ, ω_a, ω_ρ are used in the digital computer program. However, as supplied to the computer program listed in Figure 12, they are in the form G_aT, etc., where T is the sampling time interval, set at 2 ms.

Keyboard inputs permit these values to be increased or decreased by factors of two, thus affording some measure of external control over the parameters. This feature was added to the program to demonstrate a particular advantage of a digital system, namely, that is permits gains to be reset by remote control.

The digital control described above was demonstrated at the Langely Laboratories of NASA in August 1983. A unique feature of this controller is that it incorporates a development system using a relatively cheap home computer. Competitive systems use costly development systems purchased from the manufacturer of the microchip.

Current Development of Digital Control Circuit

During ongoing work, a Z80 microchip and 4K of RAM memory have been incorporated into the control box, the Z80 being slaved to the TRS-80 Model I computer. A simple modification to the computer has reduced

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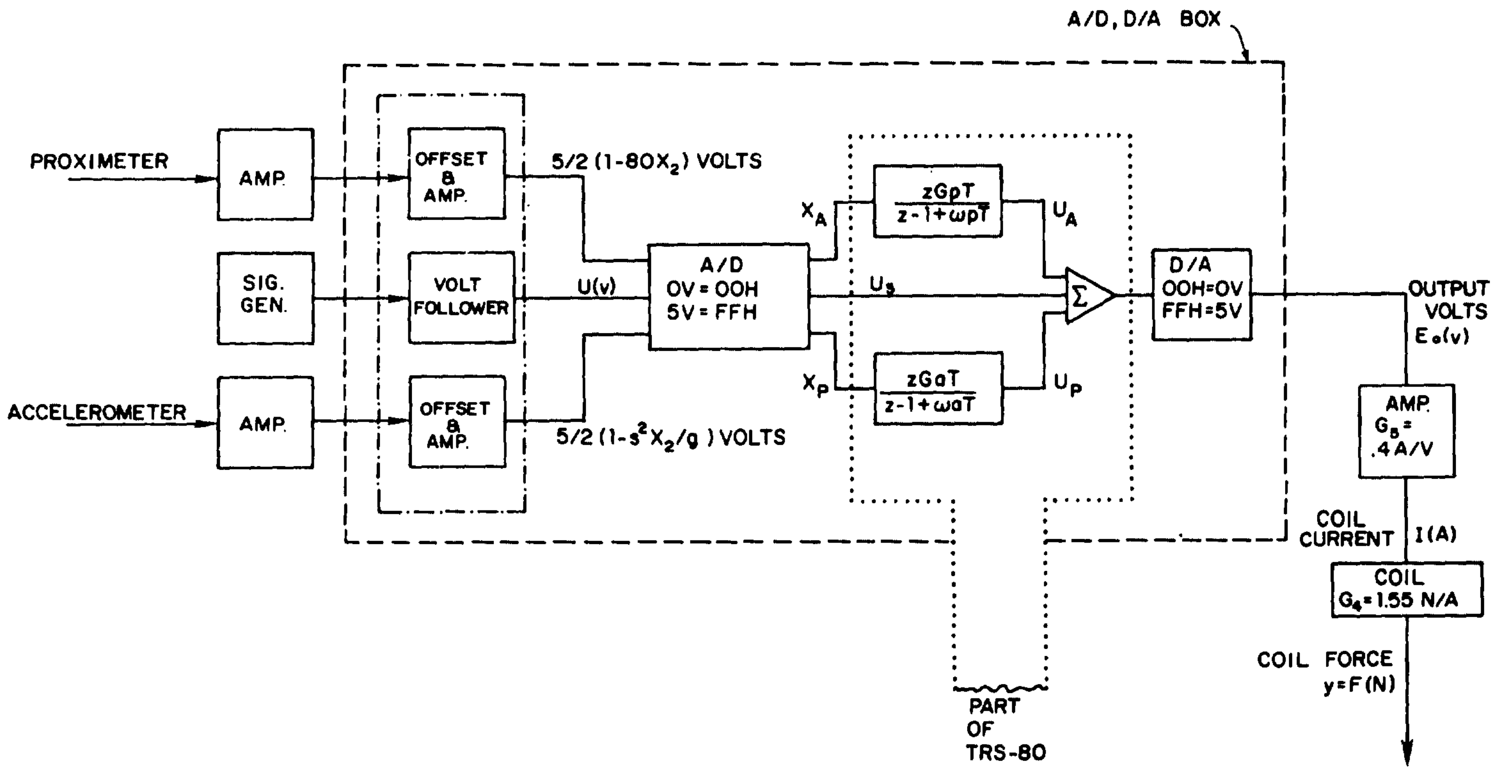

Figure 10. Digital Control System

$$H_1 \sim \frac{0.158\ G_A}{s + \omega_A} s^2 = \frac{cs^2}{s + \omega_A} \qquad (N/m)$$

$$H_2 \sim -\frac{124Gp}{s + \omega_p} = -\frac{k\omega_p}{s + \omega_p} \qquad (N/m)$$

$$H_3 = 0.62 \qquad (N/v)$$

for typical values

$\omega_a = 10(s^{-1})$, $\omega_p = 10(s^{-1})$

$c = 31$ (Ns/m), $G_a = 196$,

$k = 11.7$ (N/m) = 0.237 lb/in, $Gp = 0.94$

Digital Equations (Simple Integration)

$$u_{a_{i+1}} = u_{a_i}(1 - \omega_a T) + G_a T x_{a_i}$$

$$u_{a_{i+1}} = u_{p_i}(1 - \omega_p T) + G_p T x_{p_i}$$

$$\Sigma = u_{a_i} + u_{p_i} + u_{s_i}$$

Figure 11. Analysis of Digital Control Gains

```
        ORG     7000H
SERVO1  DI
        CALL    01C9H
        LD      C,20H   ;SET T=2MS
        LD      IX,7400H
        LD      (IX),5
        LD      (IX+1),6
        LD      (IX+2),2
        LD      (IX+3),9
        LD      HL,0            ;INIT ACCEL.
        EXX
        LD      HL,0            ;INIT. PROX.
        EXX
        CALL    DISOTA
        CALL    DISOTP
        CALL    DISGTA
        CALL    DISGTP
TIME    IN      A,(0)   ;READ STATUS
        AND     C       ;TEST FOR TIME
        JP      Z,TIME  ;RETURN IF LESS
        PUSH    BC
        IN      A,(20H) ;RESET A/D C;OCK
        OUT     (20H),A
        LD      B,(IX)
        CALL    STEP
        CALL    READ
        NEG
        LD      B,(IX+2)
        CALL    INTEG
        EXX
        OUT     (21H),A ;START PROX.
        LD      B,(IX+1)
        CALL    STEP    ;SUB. OTP*UP(I-1)
        CALL    READ    ;READ PROX.
        LD      B,(IX+3)
        CALL    INTEG   ;ADD GTA*PROX.
        PUSH    HL      ;XFER. UP
        OUT     (22H),A ;START SIG.
        EXX
        LD      B,H     ;SAVE
        LD      C,L     ;UA
        POP     DE      ;GET UP
        OR      A
        ADC     HL,DE   ;ADD UP
        CALL    OVER
        CALL    READ    ;READ SIG.
        LD      D,A     ;SIG.
        LD      E,0     ;INTO DE
        OR      A
        ADC     HL,DE   ;ADD SIG.
        CALL    OVER
```

Figure 12. Control Law Program in Z80 Machine Language

```
01140 TEST3  CP    33H
01150        JP    NZ,TEST4
01160        CALL  INGTA
01170        RET
01180 TEST4  CP    34H
01190        JP    NZ,TESTO
01200        CALL  INGTP
01210        RET
01220 TESTO  CP    4FH
01230        JP    NZ,TESTW
01240        CALL  DEOTA
01250        RET
01260 TESTW  CP    57H
01270        JP    NZ,TESTG
01280        CALL  DEOTP
01290        RET
01300 TESTG  CP    47H
01310        JP    NZ,TESTP
01320        CALL  DEGTA
01330        RET
01340 TESTP  CP    50H
01350        JP    NZ,RET
01360        CALL  DEGTP
01370 RET    RET
01380 INOTA  INC   (IX)
01390        CALL  DISOTA
01400        RET
01410 INOTP  INC   (IX+1)
01420        CALL  DISOTP
01430        RET
01440 INGTA  INC   (IX+2)
01450        CALL  DISGTA
01460        RET
01470 INGTP  INC   (IX+3)
01480        CALL  DISGTP
01490        RET
01500 DEOTA  DEC   (IX)
01510        CALL  DISOTA
01520        RET
01530 DEOTP  DEC   (IX+1)
01540        CALL  DISOTP
01550        RET
01560 DEGTA  DEC   (IX+2)
01570        CALL  DISGTA
01580        RET
01590 DEGTP  DEC   (IX+3)
01600        CALL  DISGTP
01610        RET
01620 DISOTA LD    A,(IX)
01630        AND   0FH
01640        ADD   A,30H
01650        LD    (3C48H),A
01660        RET
01670 DISOTP LD    A,(IX+1)
```

Figure 12. Control Law Program in Z80 Machine Language (continued)

```
01680        AND    0FH
01690        ADD    A,30H
01700        LD     (3C88H),A
01710        RET
01720 DISGTA LD     A,(IX+2)
01730        AND    0FH
01740        ADD    A,30H
01750        LD     (3CC8H),A
01760        RET
01770 DISGTP LD     A,(IX+3)
01780        AND    0FH
01790        ADD    A,30H
01800        LD     (3D08H),A
01810        RET
01820        END    SERVO1
```

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Figure 12. Control Law Program in Z80 Machine Language (continued)

```
00600        LD     A,H     ;HIGH BYTE OF Y
00610        ADD    A,80H   ;CONV. FOR OUTPUT
00620        OUT    (10H),A ;OUTPUT Y
00630        LD     H,B     ;REPLACE
00640        LD     L,C     ;UA
00641        POP    BC
00650        CALL   KEY
00660        LD     A,(3840H);READ KEYBOARD LINE
00670        CP     4       ;TEST FOR BREAK
00680        JP     NZ,TIME ;CONT.
00690        RST    40
00700 READ   IN     A,(0)   ;READ STATUS
00710        AND    80H     ;TEST EOC
00720        JP     Z,READ  ;RETURN IF LOW
00730        IN     A,(10H) ;READ A/D
00740        ADD    A,80H
00750        RET
00760 STEP   LD     D,H     ;U
00770        LD     E,L     ;INTO DE
00780        CALL   SHIFT   ;INIT. SHIFT
00790        OR     A
00800        SBC    HL,DE   ;SUB OT*U(I-1)
00810        CALL   OVER
00820        RET
00830 INTEG  LD     D,A     ;E
00840        LD     E,0     ;INTO DE
00850        CALL   SHIFT   ;INIT. SHIFT
00860        OR     A
00870        ADC    HL,DE   ;ADD GT*E
00880        CALL   OVER
00890        RET
00900 SHIFT  SRA    D       ;RT. SHIFT D
00910        RR     E       ;RT. ROT. E
00920        DEC    B
00930        JP     NZ,SHIFT        ;CONT. UNTIL B CLEARS
00940        RET
00950 OVER   JP     PO,CONT
00960        JP     C,MINUS
00970        LD     HL,7FFFH
00980        JP     CONT
00990 MINUS  LD     HL,8000H
01000 CONT   RET
01010 KEY    CALL   2BH
01020        CP     0
01030        JP     NZ,PRINT
01040        RET
01050 PRINT  LD     (3C00H),A
01060 TEST1  CP     31H
01070        JP     NZ,TEST2
01080        CALL   INOTA
01090        RET
01100 TEST2  CP     32H
01110        JP     NZ,TEST3
01120        CALL   INOTP
01130        RET
```

Figure 12. Control Law Program in Z80 Machine Language (continued)

internal RAM memory from 48K to 32K, leaving a "hole" in internally decoded memory of 16K. When the control box is attached to the bus, its 4K memory becomes mapped into the high address memory of the TRS-80, so that the control program can be loaded. Appropriate output codes can disconnect this memory and start the Z80, which then runs the control program independently of the TRS-80.

Capabilities of this system include the following:

1. Ability to run as an independent controller,
2. Ability to receive gain changes from the TRS-80,
3. Ability to load new control programs from the TRS-80,
4. Usefulness as a development system for control programs, and
5. One 2K RAM can be replaced by an EPROM, so that the TRS-80 will not be required for start-up.

SECTION III

SYSTEM CONSIDERATIONS

Our original conception was that considerable emphasis must be placed on determining optimum locations for dampers. However, it now seems to be evident that the typical large space structure will undergo considerable modifications and additions during its life, so that optimization of damper locations for any given configuration makes little sense.

Our present concept is that a general purpose damper should be developed, controlled by an individual digital system, whose control law can be dictated by a central computer. Under such a system, the only fixed parameters would be the value of the proof mass and its permissible double amplitude. Given these constraints, the permissible damping factor c can be determined for any given structural amplitude and frequency. Thus assuming a control law which rolls off suitably at low frequencies, the permissible structural amplitude should be only slightly less than the permissible double amplitude of motion of the proof mass.

Following this thinking, we intend to emphasize the development of more sophisticated control laws, paying special attention to the reduction of resonance peaks now present. We also intend to investigate the consequences of "bumping," i.e., of allowing the proof mass to strike the stops. In particular, we want to be sure that no limit cycle motions are possible, in which the proof mass repeatedly strikes the stops.

Figure 13 shows the hypothetical control configuration for a large space structure in which the inertial (or proof-mass) dampers are individually controlled, but are connected to a central computer, so that they can be reprogrammed as required.

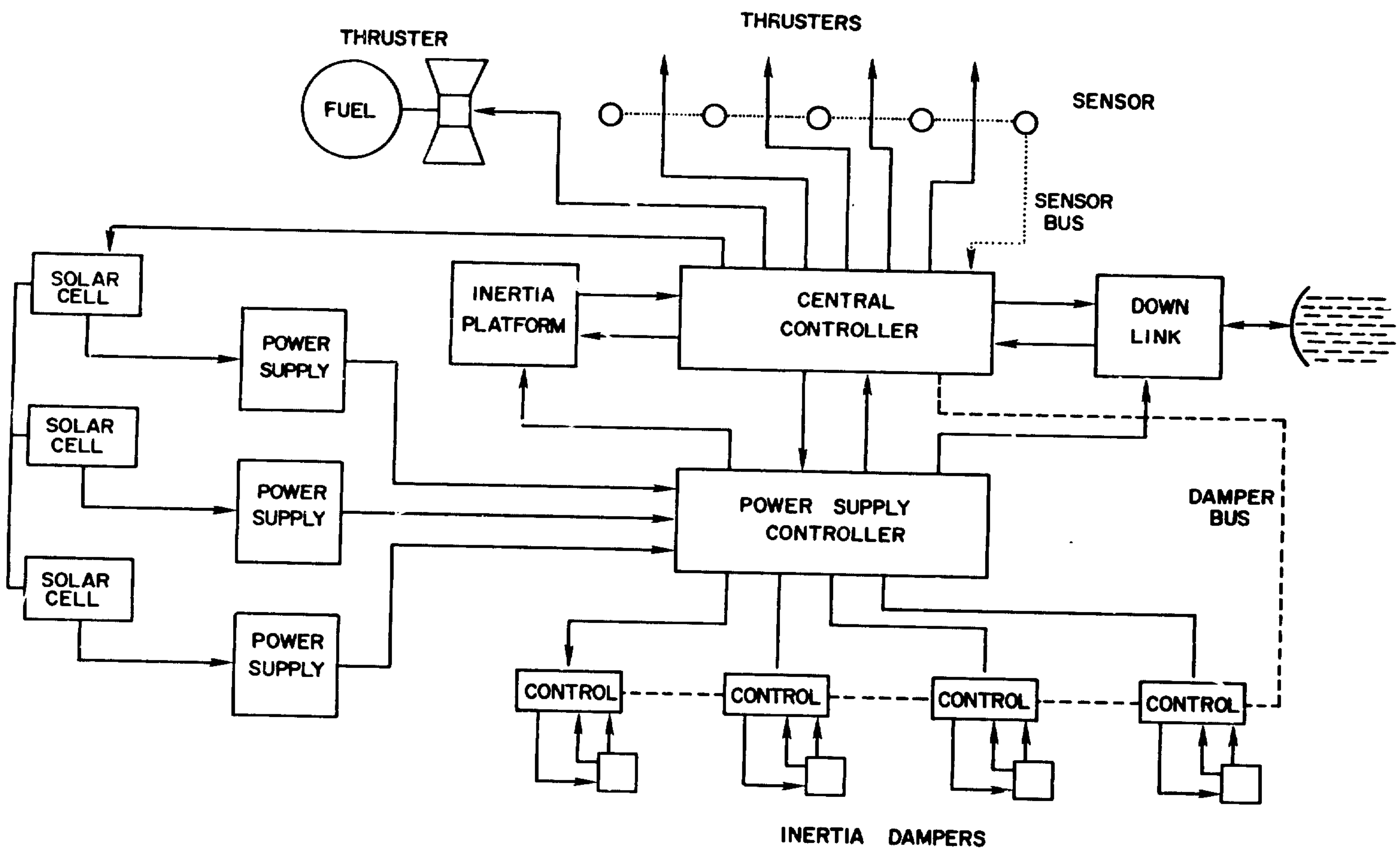

Figure 13. Hypothetical Control Configuration for Large Space Structure with Dampers

SECTION IV

PLANS FOR REMAINDER OF PERIOD

During the remainder of this period, the adapter box, presently containing wire-wrapped A/D and D/A converters, will be modified by installing a Z80 microprocessor and associated memory. This will demonstrate the concept of the individual damper which can be reprogrammed from a central computer (the Radio Shack TRS-80 Model I in this case).

At the same time, work on development of improved control laws will continue. This work will constitute part of the doctoral dissertation to be presented by Mr. Mallette.